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Experimental research on development of the controllable disturbances in the wake at supersonic flow around the plate

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THE DEVELOPMENT of the artificial disturbances in the boundary layer on the flat part of a plate, the boundary layer on the opposite wedge (model stern) behind a fan of expansion waves and the wake was investigated at Mach number 2.

1. Introduction

RESEARCH ON the flow in the wake behind an object is the important problem of aerodynamics. The base drag of bodies of revolution at supersonic speeds can be up to 30% of their complete drag (and particularly for cones – up to 50%; MIHALEV [1]; KOVENYA and LEBEDEV [2]), i.e. the flow in a wake can determine the aerodynamics of the flying apparatus. In addition, the value of the base drag can differ by more than 100% at laminar and turbulent regimes (MIHALEV [1]). Incidentally the condition of the boundary layer on a streamlined body renders influence on the position of transition in the wake.

In the system "boundary layer – wake" the process of turbulence origin in the wake behind a body has been investigated rarely so far. In the experiments (BEHRENS [3], DEMETRIADES [4], BEHRENS and KO [5], BEHRENS *et al.* [6], MCLAUGHLIN *et al.* [7], MCLAUGHLIN [8], LYSENKO [9–11]) on the stability of a wake at supersonic flow, the development of the natural disturbances is studied, therefore there are not the enough complete spatial characteristics of the wave field of oscillations. These characteristics can be obtained at the study of the controllable artificial disturbances, simulating the process of development of the natural ones (KOSINOV and MASLOV [12]). While there are many works (KOSINOV and MASLOV [12], KOSINOV *et al.* [13–15] and other), in which development of the artificial disturbances in a supersonic boundary layer was studied, the works on development of the artificial oscillations in a supersonic wake, on the whole, are absent. The main limitation of application of the method of controllable oscillations at the research on wave processes in a wake is the non-uniformity of flow, that hinders the definition of wave characteristics of unstable disturbances, however the wave approach in a number of cases can be applied. In particular, in a quasi-two-dimensional task the non-uniformity of flow is present along a flow only, then it is possible to determine wave spectra on transversal wave number, and in linear approximation – to determine the transmission characteristics on wave numbers. Thus, the practical implementation of controllable experiments in a wake depends on the flow character.

According to LEES and GOLD [16], in a wake both symmetric (varicose) and antisymmetric (sinuous) disturbances can develop. And according to theoretical work by CHEN *et al.* [17], in the supersonic wake the two-dimensional waves of antisymmetric mode are the most unstable. Their phase velocity is about 0.8. The two-dimensional character of the most unstable disturbances of this mode remains at sub-, super- and hypersonic speeds of a flow. For the symmetric mode at supersonic speeds the three-dimensional waves are the most unstable, and the phase velocity increases with increasing Mach number. At $M = 2$ it is approximately equal to 0.6. The symmetric mode (by character of instability and values of phase velocity) is similar to the eigen-disturbances of supersonic boundary layer.

The influence of disturbances in the model boundary layer on disturbances in the wake is obviously possible, as their wave characteristics are close. At the same time it is necessary to take into account the circumstance, that the formation of a wake is accompanied by non-uniformity of flow in longitudinal direction, that results in the change of discrete spectrum on wave numbers to the continuous one.

The purpose of the present work was the study of development of the artificial disturbances (initiated on the surface of a flat plate) in the system "boundary layer on the flat part of a plate – boundary layer on the opposite wedge (model stern) behind a fan of expansion waves – wake" at supersonic free-flow velocities.

2. Research methods and equipment

The present experiments were carried out in the wind tunnel T-325 (BAGAEV *et al.* [18]) at free-flow Mach number $M_\infty = 2.0$, unit Reynolds number $Re_{1\infty} = 5.4 \cdot 10^6 \mathrm{m}^{-1}$, flow stagnation temperature 290 K.

As the basic test model (model 1), an insulated steel symmetric flat plate (Fig. 1) of 80 mm length (from the leading edge up to the back edge), 10 mm thickness, 200 mm width, having the bow and stern as wedges with bevel half-angle of the leading and back edges of 14°, was used. The length of both the bow and stern parts was 20 mm. For realization of an additional experiment, the model 2 (modified model 1) was used. For model 2 the stern looked like the opposite wedge with bevel half-angle of 10°. Accordingly, the length of the stern part has increased from 20 up to 28 mm, and the length of the central site has decreased down to 32 mm (on model 1 it was equal to 40 mm). Other differences between models 1 and 2 were absent.

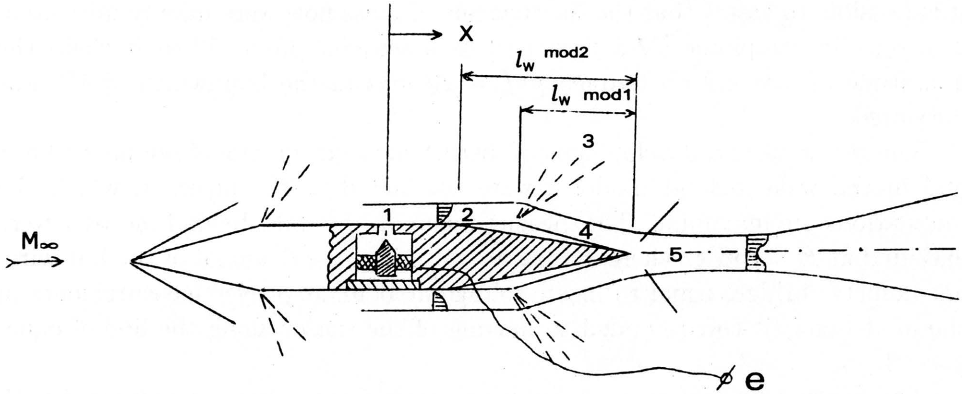

FIG. 1. The scheme of the model flowing around: (1) source of controllable disturbances, (2) plate flat-part boundary layer, (3) fan of expansion waves, (4) opposite-wedge boundary layer, (5) wake.

The plate was fixed rigidly to the lateral walls of the wind tunnel's test section and was established under a zero angle of attack. Inside of the model in the center, a source of controllable disturbances (similar to KOSINOV *et al.* [15, 19]) was placed. For excitation of the disturbances, the high-frequency electrical discharge device was used. The artificial disturbances penetrated through the hole of 0.4 mm diameter, 40 mm from the leading edge, into the boundary layer on the top surface of the plate. At glow discharge, in the interspace between an electrode and model surface (under the hole on the plate surface), the pressure and temperature oscillations arose, which disturbed the boundary layer, penetrating into it through this hole. A design and detailed description of the disturbance generator are adduced in KOSINOV *et al.* [19]. From the hole of disturbance generator, the longitudinal x and transversal z coordinates were measured.

The scheme of ignition of high-frequency electrical discharge consists of the generator of signals G3-112/1, power amplifier, raising transformer and electrodes (this scheme is described also in KOSINOV *et al.* [19]). The process of glow discharge was inspected by the oscillograph C1-96.

In the first section $x = 8$ mm, measured in the boundary layer, the parameter of excess of the maximum disturbance amplitude above the natural background was about 10, and in the wake it was about 2. The results presented in the paper are obtained for oscillations of frequency $f = 20$ kHz.

For measurement of disturbances, the constant-temperature hot-wire anemometer and the probe (with the tungsten wire of diameter of 5 microns and length of 1.2 mm) were used. The overheating of the probe wire was 0.8, and therefore it is possible to assert that the fluctuations of mass flow were mainly measured. The selective amplifier U2-8 was used as a frequent filter. With its help the amplitude of a signal on frequency $f = 20$ kHz in the bandwidth of 1% was measured.

The researches on development of disturbances in the model boundary layer and in the wake behind model 2 were conducted in the layer, in which the fluctuations are maximum. The measurements in the wake behind model 1 were executed at $E = \text{const}$, where E – mean voltage in the diagonal of the hot-wire-anemometer bridge, equal to mean voltage at boundary-layer measurements in the model end (it corresponded to moving of the sensor along the line of equal mass flow).

The fluctuating and average characteristics of the flow were measured with the help of the automated measuring system (KOSINOV *et al.* [19]) of the wind tunnel T-325. The fluctuating and average hot-wire voltages were recorded by a computer (DVK-3.2) using a ten-bit amplitude-digital converter (ADC) with 1 MHz reading frequency. The ADC was started synchronously with the generator setting the frequency of the introduced disturbances. For increase of the signal/noise ratio, the synchronous summation of a signal on 200 realizations was carried out. The time length of each realization was 200 microseconds. The averaged oscillograms of a fluctuation signal were controlled during the experiment. It allowed to determine the bounds of the introduced wave packet on z rather precisely. In experiments the oscillograms in several cross-sections on x were measured.

The complete spectral processing of digital oscillograms was carried out by an IBM PC. For spectral processing of experimental data, the discrete Fourier-transformation was used

$$e_{\beta\omega}(x,y) = \frac{2}{T}\sum_{j,k} e(x,\, y,\, z_j,\, t_k)\exp\left(-i\left[\beta z_j - \omega t_k\right]\right),$$

where $e(x, y, z_j, t_k)$ is the pulsation signal from the hot-wire anemometer, averaged through realizations, T – the length of realization in time, $\omega = 2\pi f$ – circular frequency of a disturbance, β – wave number in z-direction, j – list on coordinate z, k – list on time. Amplitude and phase of disturbances (in their notation we shall omit the index ω, as the selective amplifier was adjusted to one frequency) were found from the formulas

$$A^*_\beta = \{\mathrm{Re}^2[e_{\beta\omega}(x,y)] + \mathrm{Im}^2[e_{\beta\omega}(x,y)]\}^{0.5},$$

$$\Phi_\beta = \mathrm{arctg}\{\mathrm{Im}[e_{\beta\omega}(x,y)]/\mathrm{Re}[e_{\beta\omega}(x,y)]\}.$$

The wave-to-the basic flow inclination angle $\chi = \text{arctg}\,[\beta/\alpha_r(\beta)]$, where the wave number in x-direction α_r was determined from the relation $\alpha_r(\beta) = \Delta\Phi_\beta(x)/\Delta x$ due to linear phase dependence $\Phi_\beta(x)$.

The phase velocity of disturbances was determined by the formula $c_x = \lambda_x f/U_e$, where $\lambda_x = 2\pi/\alpha_r$ is the wavelength of a disturbance, U_e – flow velocity at the layer border.

3. Results

In conformity with the conditions of flowing round the model, the boundary-layer flow had a non-uniformity streamwise, connected with two fans of expansion waves. The first fan started near to the place of change of the nose wedge to the central (flat) model site, the second one – near to the place of change of the central site to the opposite wedge. In KOSINOV *et al.* [14] (this work was executed on the model "cone–cylinder") it was found, that behind a fan of expansion waves the pressure becomes constant at the distance equal to twenty values of the boundary-layer thickness. For conditions of the present experiments, it corresponds to about 6 mm from the first "fracture" of the model, moreover for the model "wedge–plate" this distance should be even smaller. Thus, in the present experiments the source of disturbances was placed in gradientless (on x) flow. In this case we should expect the development of disturbances on the central part of model, similarly to the results of experiments in the boundary layer on the flat plate (KOSINOV *et al.* [14]).

In this work, the development of controlled disturbances was investigated on 3 ranges: (I) on the central (flat) part of the plate, (II) at passage through a fan of expansion waves and on the opposite wedge, and (III) in the wake.

3.1. On the central (flat) part of the plate

For definition of the character of development of the introduced spatial wave packet ($f = 20$ kHz), the measurements of distributions (on transversal coordinate z) of mass-flow fluctuations in the boundary layer were executed at $x = 8, 13$ and 18 mm. The analysed range corresponds approximately to one disturbance wavelength. After the data processing, the wave amplitude-phase spectra on β and dispersion relations $\alpha_r(\beta)$ and $\chi(\beta)$ were obtained. In Fig. 2 the amplitude spectra A^*_β on β for $x = 8$, 13 and 18 mm are shown, normalized by the average value of mass flow in measurement positions. Thus, it was confirmed that on the flat part of the model, as well as in case of the flat plate (KOSINOV *et al.* [15]), the inclined disturbances with $\beta = \pm 1$ rad/mm are the most unstable. The asymmetry in spectra is caused by properties of the disturbance generator; this is confirmed after normalization of, amplitude spectra on β by the initial

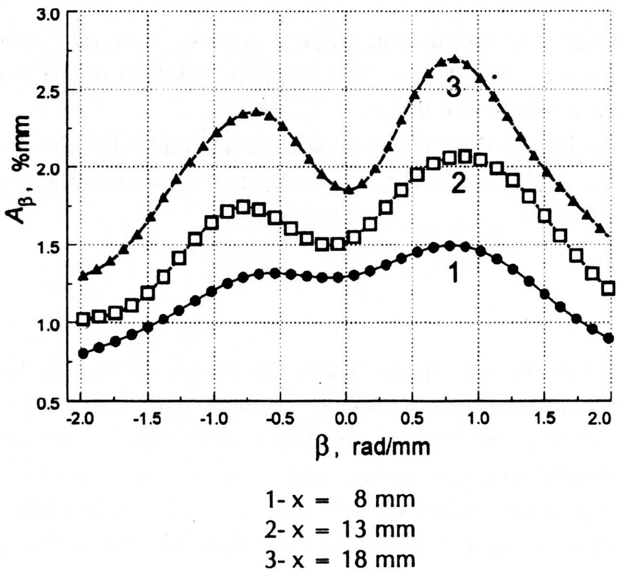

FIG. 2. Amplitude spectra for $x = 8$, 13 and 18 mm (flat part of model).

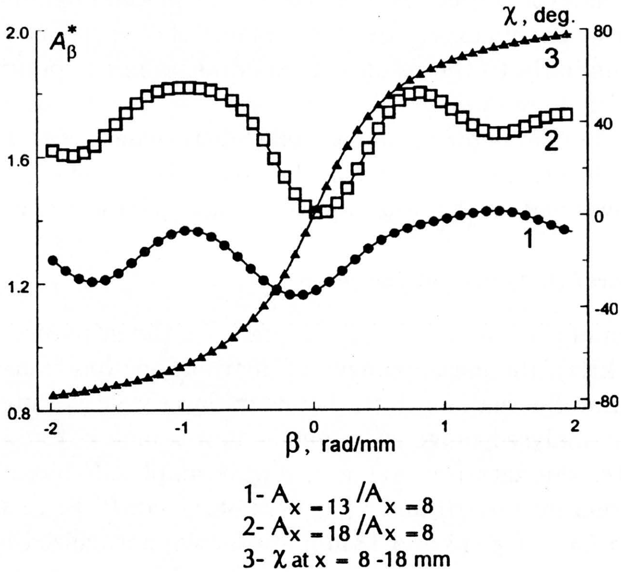

FIG. 3. Normalized amplitude spectra for $x = 8$, 13 and 18 mm, and dispersion dependence for $x = 8$–18 mm (flat part of model).

the initial(at $x = 8$ mm) spectrum. It is demonstrated in Fig. 3, where the examples of normalized amplitude spectra A^*_β for $x = 13$ and 18 mm (curves 1 and 2), depending on β, and the dispersion dependence $\chi(\beta)$ (curve 3) are given, where χ is the angle of the inclination of the wave front to the basic flow. It was found, that on the flat part of the plate the phase velocity of propagation of disturbances $c_x \approx 0.55$, the wave number in the streamwise direction $\alpha_r \approx 0.45$ rad/mm, and the inclined disturbances with $\chi \approx 60°$ are the most unstable. All the data, obtained in the boundary layer on the flat range of the plate, are in a good agreement with the researches on a flat plate (KOSINOV and MASLOV [12], KOSINOV *et al.* [13, 15]).

3.2. At passage through a fan of expansion waves and on the opposite wedge

The measurements of distributions of controllable oscillations on z on the opposite wedge are executed at $x = 25.2$; 30 and 35 mm. In Fig. 4 the amplitude spectra A^*_β on β for these values of longitudinal coordinate, normalized by the initial spectrum of disturbances at $x = 8$ mm, are exhibited. Figure 4 (curve 1, $x = 25.2$ mm) shows the considerable stabilization of disturbances at passage through a fan of expansion waves (i.e. at the negative gradient of pressure).

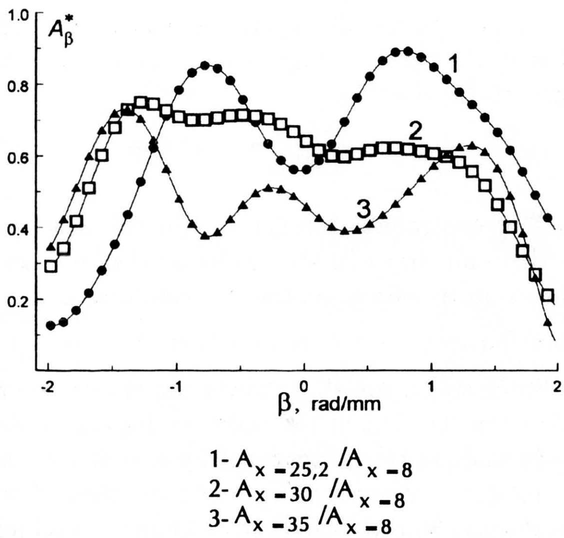

FIG. 4. Normalized amplitude spectra for x=25.2; 30 and 35 mm (opposite wedge).

This statement is in a complete conformity with the results of the theoretical works (GAPONOV and MASLOV [20], LYSENKO [21 – 22], GAPONOV and PETROV [23]) and the experiments (KOSINOV *et al.* [14], GAPONOV, KOSINOV *et al.* [24]), in which the investigations were carried out on the "cone-cylinder" model. As a whole, on the opposite wedge after the fan of expansion waves (in the range $x = 25.2 - 35$mm), a certain decrease of the disturbance level was found. The obtained data correspond to the statements of GAPONOV and PETROV [23], GAPONOV, KOSINOV *et al.* [24] that the stability, arising under influence of the flow turn, is kept at large distance after its end, and correspond to the conclusion of KOSINOV *et al.* [14] that at some distance after recovery (after flow turn) of a boundary layer to the equilibrium condition, it remains stable. However it is important to notice, that the work by GAPONOV and PETROV [23] and part of the work by GAPONOV, KOSINOV *et al.* [24] are theoretical, and in experimental work by KOSINOV *et al.* [14] and in the experimental part of the work by GAPONOV, KOSINOV *et al.* [24] the "cone-cylinder" model is analysed.

As it was already indicated, the measurements of distributions on z were executed in a maximum of controllable fluctuations across the boundary layer. Before the turn of flow ($x = 20$ mm) this maximum was at $\dfrac{\rho U}{\rho_\infty U_\infty} = 0.9$, after the turn – at $\dfrac{\rho U}{\rho_\infty U_\infty} = 0.55$. It was found, that the flow was homogeneous on z down to $x = 30$ mm, and at $x = 35$ mm the essential (up to 5–10% concerning the mass flow in the free stream) distortion of flow in transversal direction was revealed, which was close to periodic. This periodicity corresponded approximately to 2 mm. Probably, the appearance of such non-uniformity on z is caused by influence of the wake.

3.3. In the wake

As measurements of controllable oscillations in the near wake behind the model have shown, the scale and non-uniformity level of flow in transversal direction remained the same, as well as on the opposite wedge at $x = 35$ mm. The measurements of distributions on z were executed at $\dfrac{\rho U}{\rho_\infty U_\infty} = 0.55$. In Fig. 5 the normalized amplitude spectrum A^*_β on wavenumber β in the wake for $x = 43$ mm is presented. One can see that in the wake, additional peaks in spectra on β occur. The data, obtained in this experiment for $x = 48$ mm, have turned out to be distorted, as this cross-section is already in the zone of strong nonlinear development of disturbances in the wake (and at about $x = 53$ mm, as the oscillograms have shown, in the wake the laminar-turbulent transition starts). This is why the additional investigation on changed model (model 2, with shorter flat part of the plate – 32 mm instead of 40 – and longer model stern – 28 mm instead of 20) was carried out to observe more confidently the development of disturbances in a wake. Such change of model stabilizes these disturbances. At first, as it was shown in the paper by LYSENKO [11], with increase of the length

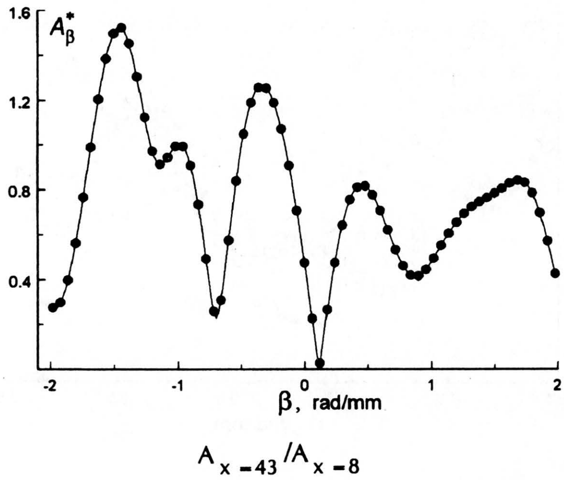

FIG. 5. Normalized amplitude spectrum for $x = 43$ mm (wake, model 1).

of the model stern part, the position of transition in a wake displaces downstream, and the stability of this wake slightly increases. Secondly, the decrease of bevel angle of the stern part (when it is an opposite wedge) from 14° to 10° and, naturally, the flow turn angle before a wake leads to reduction of intensity of the appropriate shock wave, which can be the generator of disturbances (similarly to the fan of expansion waves, which in works by KOSINOV *et al.* [14] and GAPONOV, KOSINOV *et al.* [24] resulted in the growth of sound oscillations). And with decreasing of shock-wave intensity the generated disturbances can decrease accordingly. Thus, the above-stated factors should result (at investigation on model 2) in considerable lengthening of the laminar site of disturbance development in the wake and transition delay.

In Figs. 6–7 the amplitude spectra A^*_β on β and χ in the wake behind the model 2 for $x = 41.5$; 51.5 and 61.5 mm, normalized by the wave spectrum at $x =$ 9 mm are presented. These results demonstrate the evolution of disturbances in the wake and differ from the data shown in Fig. 5. At first, the relative amplitude is essentially (6–7 times) less than for the first model; secondly, spectra are more smooth, with smaller modulation of amplitude. Apparently, it is connected with changes of the flow character, becoming less unstable, and with essentially smaller non-uniformity of flow in transversal direction. In Fig. 8 the phase spectra Φ^*_β on β for $x = 41.5$; 51.5 and 61.5 mm are presented. These spectra resemble the phase spectra in the boundary layer. The dependences 2 and 3 are similar to each other, that proves the similar correspondence of α_r and β.

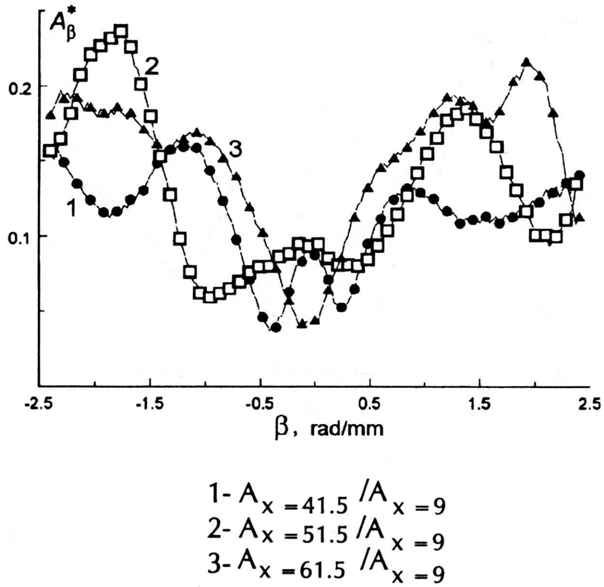

FIG. 6. Normalized amplitude spectra for $x = 41.5$; 51.5 and 61.5 mm (wake, model 2).

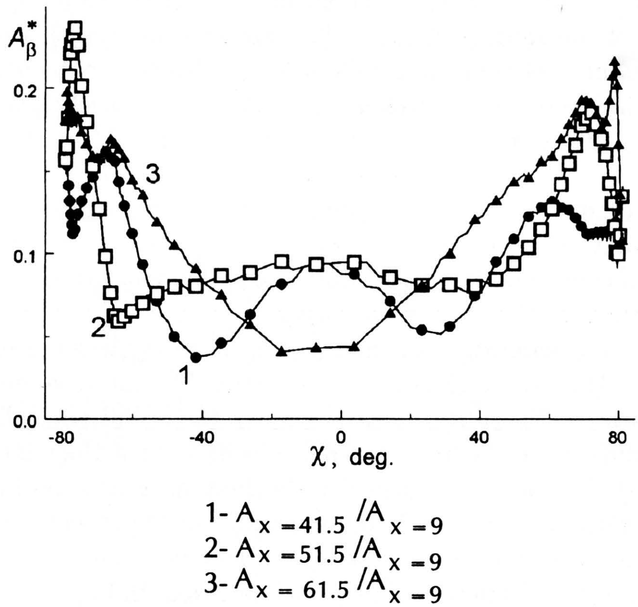

FIG. 7. Normalized amplitude spectra on the angle of inclination of wave vector to a flow for $x = 41.5$; 51.5 and 61.5 mm (wake, model 2).

The estimation of the phase velocity of disturbances in the wake ($x = 51.5$–61.5 mm), given in Fig. 9 (curve 1) depending on the angle of inclination of a wave vector to the flow, allows to conclude that in the experiments discussed the evolution of the wake symmetric mode is mainly observed, which is close, on phase velocities, to the eigen-waves of supersonic boundary layer. The curve 2 in Fig. 9, represented the dependence of amplitude of waves on the angle of inclination (for $x = 61.5$ mm), shows that the disturbances with angles of inclination more than 60° have the greatest relative amplitude. More complex evolution of disturbances in the wake behind the first model can be connected with greater instability and non-uniformity of flow. In principle, in any special case, the last circumstance can result in strong detuning of disturbances on wave numbers in longitudinal direction and generation of quasi two-dimensional antisymmetric mode.

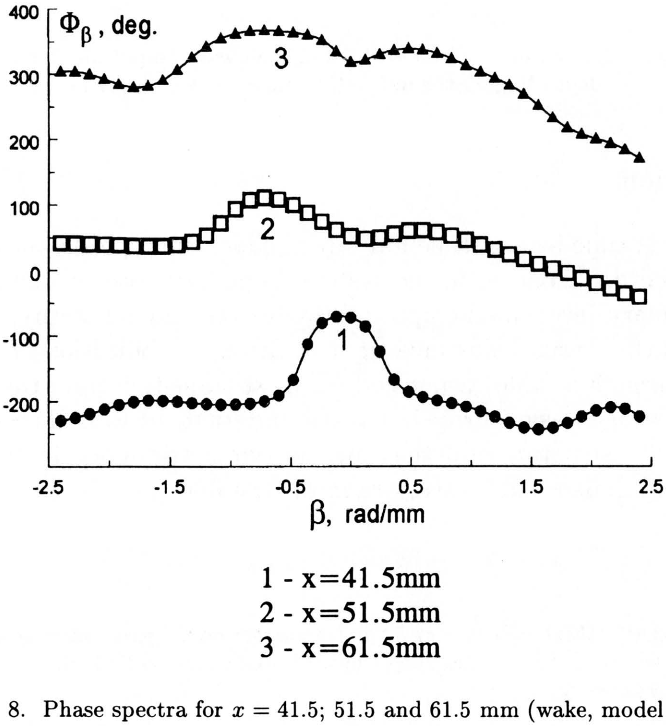

FIG. 8. Phase spectra for $x = 41.5$; 51.5 and 61.5 mm (wake, model 2).

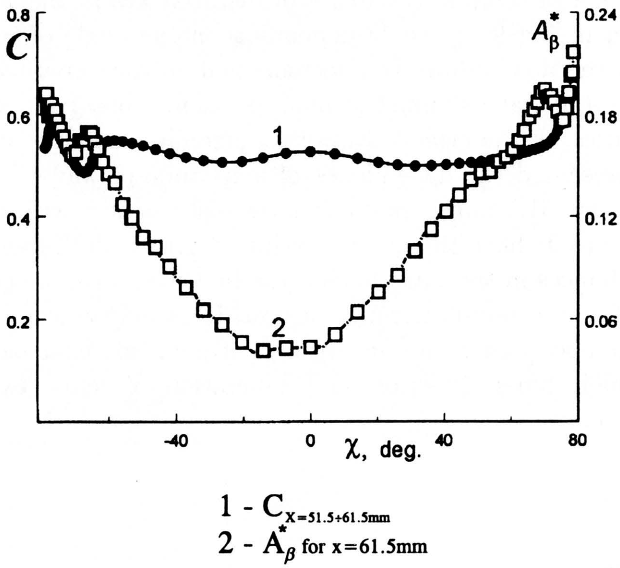

FIG. 9. Phase velocity (for $x = 51.5 - 61.5$ mm) and wave amplitude (for $x = 61.5$ mm) depending on the inclination angle (wake, model 2).

4. Conclusions

For the first time by experimental way at supersonic speeds, the development of the artificial disturbances in the system "boundary layer on the flat part of a plate – boundary layer on the opposite wedge (the model stern) after a fan of expansion waves – wake" was investigated. Strong stabilization of disturbances at passage through a fan of expansion waves at transition from the flat plate to the opposite wedge was confirmed. It was found, that the wake disturbances have a complex wave structure and that for the symmetric mode in the supersonic wake the three-dimensional waves are most unstable.

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